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Hydraulic Testing of Polymer Matrix Composite 102mm Tube Section Technical Report

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The objective of this report is to hydraulically pressurize the internal diameter of one (1) 102mm Polymer Matrix Composite (PMC) over-wrapped cylinder up to 25,000 pounds per square inch (psi). During pressurization, in real time, collect and store pressure and strain data simultaneously. Strain data must be captured from the inside diameter of the oil filled metallic cylinder and from the outside diameter of the composite over-wrap material. Test data is to be provided to the customer and stored for further analysis.

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Table of Contents

List of Figures

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List of Tables

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Objective

To hydraulically pressurize the internal diameter of one (1) 102mm Polymer Matrix Composite (PMC) over-wrapped cylinder up to 25,000 pounds per square inch (psi). During pressurization, in real time, collect and store pressure and strain data simultaneously. Strain data must be captured from the inside diameter of the oil filled metallic cylinder and from the outside diameter of the composite over-wrap material. Test data is to be provided to the customer and stored for further analysis.

Introduction

The test specimen was machined to a 15" height with seal pockets on each end. The seal pockets house the top and bottom enclosures. A 12" undercut was machined on the outside diameter for PMC over-wrapping. The test specimen evaluated had an average OD of 5.1366" which resulted in a nominal composite wall thickness of 0.2183".

Four strain gages were placed 90 degrees apart from each other on the test specimen bore to measure strain in the hoop direction. Axial location of the interior strain gages was in the center of the test specimen. On the exterior surface of the test specimen, four rosette strain gages were placed in the same radial and axial location on the outside PMC material.

Each interior hoop direction strain gage contained a three-wire set-up for ease of balancing the bridge. Each internal strain gage wiring system was insulated from the test specimen due to grounding loops, which cause noise in the test data, Polyethylethylketone (PEEK) material was utilized for this purpose. 1080 series steel piano wire of 0.040" in diameter was silver soldered to cylindrical 4340 steel connector pin housings. Harris brand "Stay-Clean" liquid flux and "Stay-Brite" silver solder was used by bringing the wire and pin housing to 500^{o} F and soldering the two together. The silver soldered sub-assembly was placed inside the cylindrical shaped PEEK insulating seal. The entire assembly was placed inside a counterbore in the top and bottom enclosures. Located at the bottom of the counterbores was a disc of PEEK material separating the silver soldered assembly from the enclosure. O-ring seals were used between the connector pin and the inside diameter of the PEEK material. Another o-ring was used for sealing pressure between the outside diameter of the PEEK material and the counterbore in the top and bottom enclosure. All wires for the respective internal strain gages were connected to piano wires. As a result, there were six wires running through the top and bottom end closures in order to successfully read the four internal strain gages. Placed over the top and bottom end closures were cover plates, which accept and protect the strain gage wires. The set-up enables the wires to be connected to the computerized data acquisition system, located outside the test cell.

For testing conducted in 2005 for similar composite cylinders [a], strain data was successfully collected on the interior strain gages and correlated well with the exterior gages. This test was conducted several times around the 2002 - 2005 time frame as a screening test for different polymer composite overwrapped cylinders but the data was never published. The goal of the test being to see if there was a lag between the internal and external strain gages. Any lag between the gages would indicate that there was a gap between the steel substrate and the composite overwrap.

The cylinder under study this time was produced under the Phase I of the "Low-Cost Low Temperature Processed Polyorganosiloxane Armament Composites with High Temperature Durability" SBIR (contract number WQKN-16-0002). The goal of the SBIR is to develop a composite material that can be processed at a low

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temperature and still be used at 1000 °F. Normally a composite cannot be used above its cure / melt temperature. This causes issues as thermoset composites become soft during cure and don't assume their final shape until after cure and they have a very low coefficient of thermal expansion (CTE) compared to metals. So during cure of a thermoset composite over a steel substrate the steel would expand as the temperature is increased, the composite would soften allowing the expansion and then set its final shape at the cure temperature. As the steel cools it shrinks but the composite doesn't forming a gap. The material developed under this ILIR can be moisture cured at room temperature so the difference in CTE between the steel and composite should not result in a gap forming after cure.

Figure 1: Composite Cylinder Testing Conducted in 2004 [a]

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Hardware and Method

The entire test fixture assembly was placed on top of riser blocks inside the one million pound press located in test Cell #3. The use of the INSTRON controlled head in test Cell #3 allowed for a pre-programmed pressurization of the test specimen to the details located in the test plan [b], this allowed for a consistent ramp rate of pressure for a steady strain trace. The INSTRON machine was programmed for a three cycle interval, at 25,000 psi each cycle, with a one second hold at the test pressure before pressure was released [c].

A slaved fixture in test Cell #3 was utilized to connect the test specimen by means of a threaded hole in the top closure (Figure 2). High pressure is generated by displacing oil within the slaved fixture by means of a 2.5" diameter ram capable of a 10" stroke with over 550 Kips of force acting on the ram. The high pressure oil was delivered to the PMC test specimen in the one million pound press by flexible high pressure piping.

Figure 2: PMC Test Setup in Cell #3

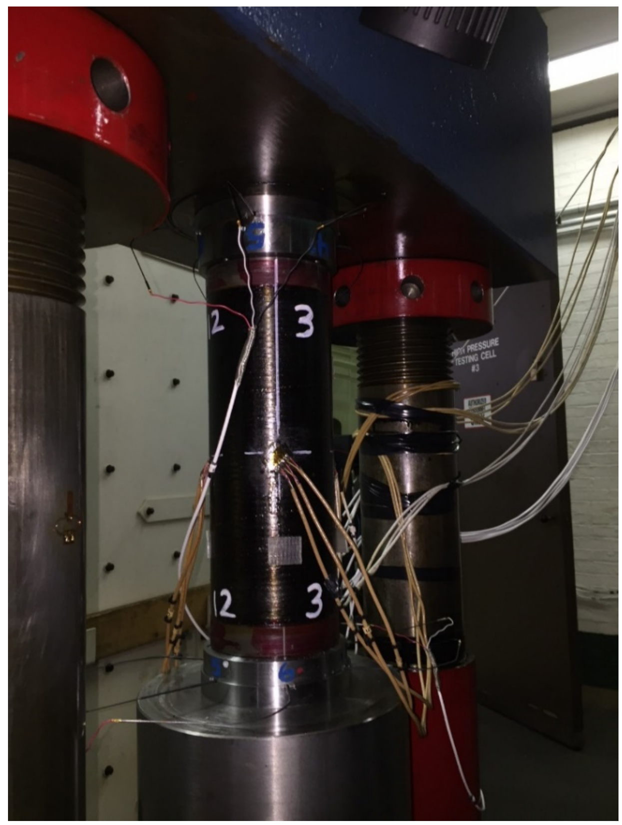

Figure 3: PMC Test Setup in Cell #3 Close

Figures 2 & 3 show the extensive wiring required for the 19 channels of data for this test. There were a total of eighteen (18x) ¼ bridge strain gage circuits (with three wires each), as well as a pressure transducer. The data was collected on an expandable DEWESoft brand 24 channel time synchronized system at 100 Hz.

To verify pressures seen during testing the pressure transducer used was calibrated by following internal procedures using the dead weight tester [d]. The dead weight tester was produced by American Instrument and

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capable of calibrating transducers up to 100,000 psi (See Figure 11). A dead weight tester is a NIST-traceable device that floats precision weights to pressurize a fluid to a specific pressure that a transducer can be calibrated to. The pressure transducer used in Cell #3 was a 50,000 psi capacity SN 1347589. For the 102mm PMC test specimen the transducer was calibrated to 30,000 psi.

After verifying the INSTRON programming by blind pinning the high pressure piping and verifying functionality of the three cycles at target pressure each with a one second hold, the test specimen was hooked up with the flexible hydraulic line. Upon pressurization of the first cycle the test specimen appeared to fail with a considerable audible bang. Figure 4 shows the results of a visual inspection of the test specimen after it failed to reach target pressure of 25,000 psi.

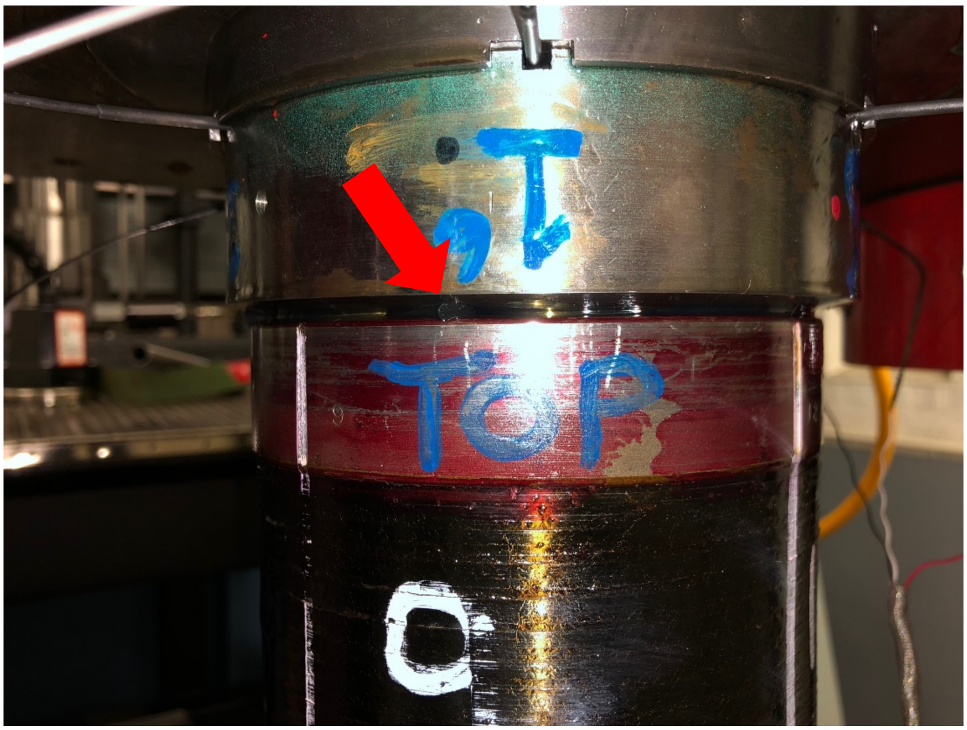

Figure 4: O-ring Extruded on Top Enclosure

Further review of the data showed the enclosure failed to hold pressure after 23,000 psi and the wedge ring extruded itself past the major diameter of the enclosure body and allowed the o-ring to be cut. Figures 5 &6 show the extent of damage from the first test.

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Figure 5: Wedge Ring Failure Shown in Tube

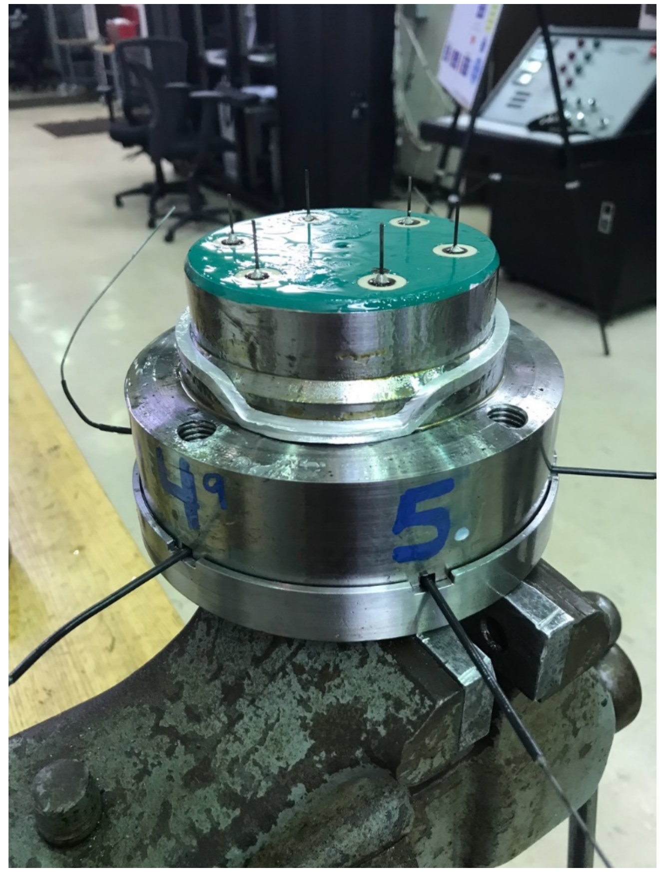

Figure 6: Wedge Ring Shown on Top Enclosure

Dimensional inspection of the test specimen showed a permanent dilation at the top seal pocket, measuring 0.060” out of round. To salvage this unique PMC test specimen, the top seal pocket was machined to accommodate the next size top enclosure that the tube lab had in stock. This resulted in cutting the top seal pocket from a nominal size of 4.240 to 4.334 to accommodate a larger enclosure. The modified fixturing resulted in only having the ability to measure interior hoop strains of two gages instead of the original four. To ensure the seal pockets would not dilate again and compromise the test specimen any further, two dilation limiting rings were manufactured to encase the outside diameter of the seal pocket area to ensure the seal would be maintained up to test pressure of 25,000 psi. See Figure 7 showing two less interior hoop and two less exterior rosette wire hookups.

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Figure 7: PMC Test Setup with Dilation Limiting Rings

Utilizing the test setup shown in Figure 7, test pressure was successfully achieved on all successive test cycles. In order to capture strain values for all hoop gages on the interior surface, there were two test setups run. For test setup #1, the interior hoop gages located at 6 and 12 o'clock were hooked up and cycled three times. For test setup #2, the interior hoop gages located at 3 and 9 o'clock were hooked up and cycled three times. Again, this had to be done in two setups because the loss of the original top enclosure with instrumentation pass through no longer fit the larger seal pocket. Table 1 shows the results of the two setups utilized.

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Test Cycle	Pressure (psi)	Position (clock)	Hoop Strain (με)		Comments
			Exterior	Interior	
1	25,414	6:00	2,870	7,091	Interior Gage Wiring Wrong
		12:00	2,815	7,276	
2	25,402	6:00	2,673	3,854	*Gage started to delaminate
		12:00	2,580	5,621	Data returned to zero
3	25,234	6:00	2,759	1,897	*Gage delaminating
		12:00	2,630	5,451	Data returned to zero
4	25,258	6:00	2,734	-43,501	*Gage not responding
		12:00	2,615	5,211	Data returned to zero
5	25,381	3:00	2,721	-6	*Gage started to delaminate
		9:00	2,837	5,464	Data returned to zero
6	25,462	3:00	2,724	-2,016	*Gage delaminating
		9:00	2,841	5,492	Data returned to zero
7	25,410	3:00	2,711	-2,456	*Gage not responding
		9:00	2,827	5,487	Data returned to zero

Table 1: PMC Strain Results

Strain Gage data inconsistent

The results shown in Table 1 display the test pressures achieved for the seven different sets of test cycles, as well as the maximum strains achieved during the cycles. The graph shown in Figure 8 has micro strain on the Y-axis and time on the X-axis as it relates to the strain gages. The data shown graphically shows a consistent trace between the interior hoop gages as well as the exterior hoop gages, with a return to initial strain. For interior locations at the 3 and 6 o'clock location, the gages had various levels of damage from the first failure to reach test pressure and lead wires being partially torn from the gage. Upon disassembly it became apparent that some gages delaminated on the inside, and the strain signal was lost over multiple test cycles. For clarity, the data recorded for the 3 and 6 o'clock locations was omitted.

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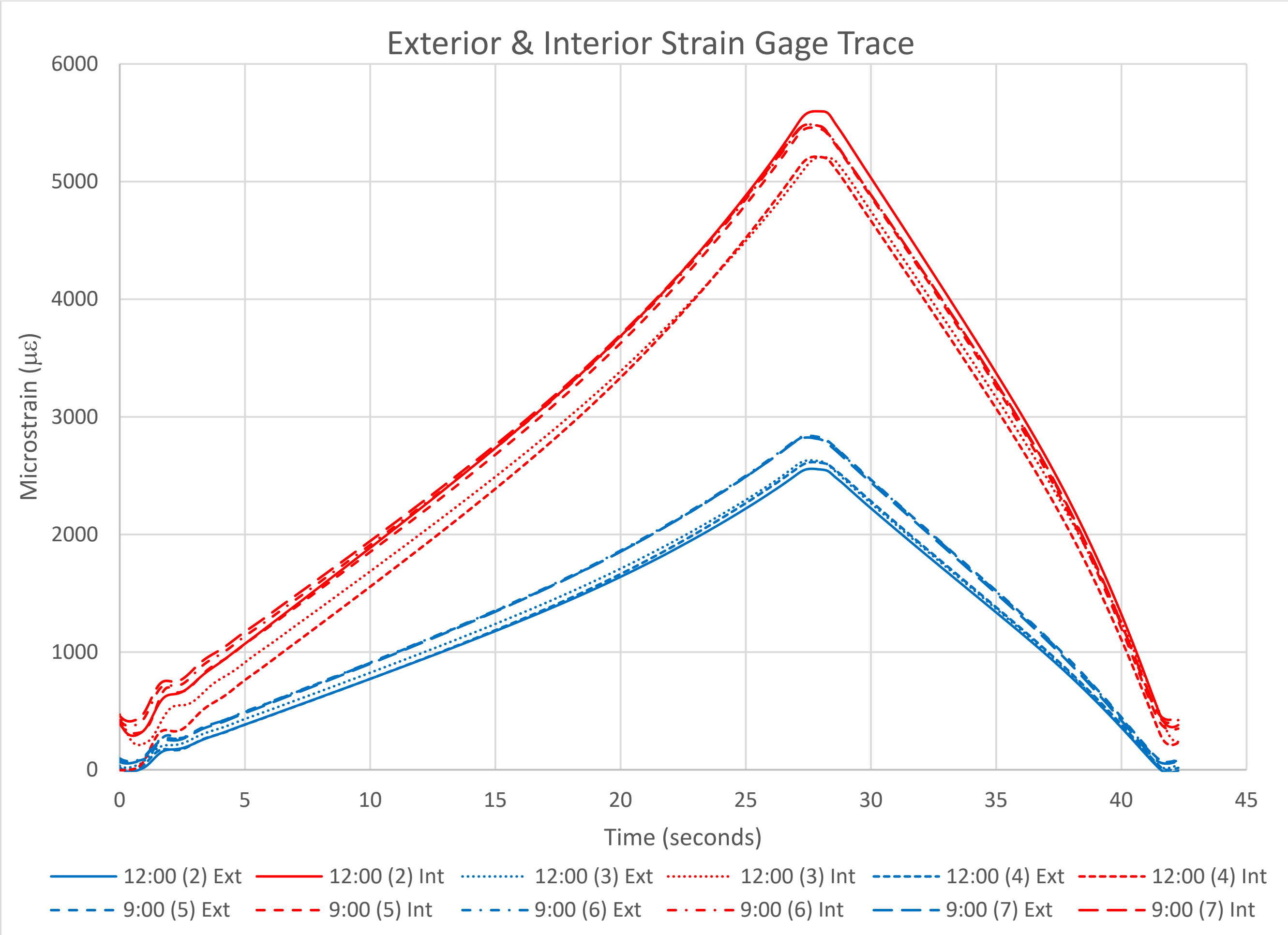

Figure 8: PMC Strain Results Shown Graphically

The raw data for the rosette strain gages and interior hoop gages is shown in Figures 9 & 10 for Test cycle 4 and 7 respectfully.

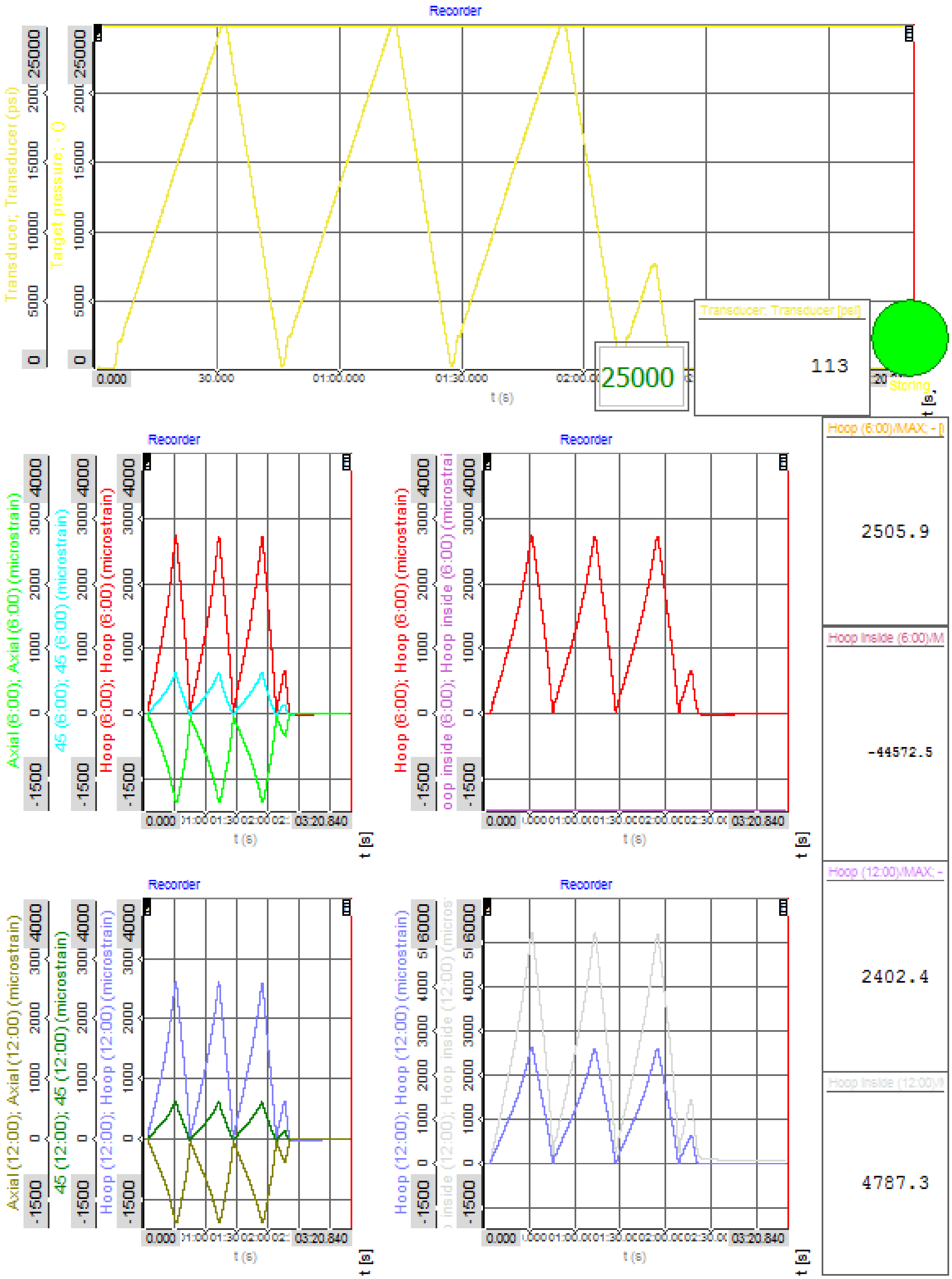

Figure 9: PMC Raw Strain Results for 6 and 12 o'clock (Test Cycle 4)

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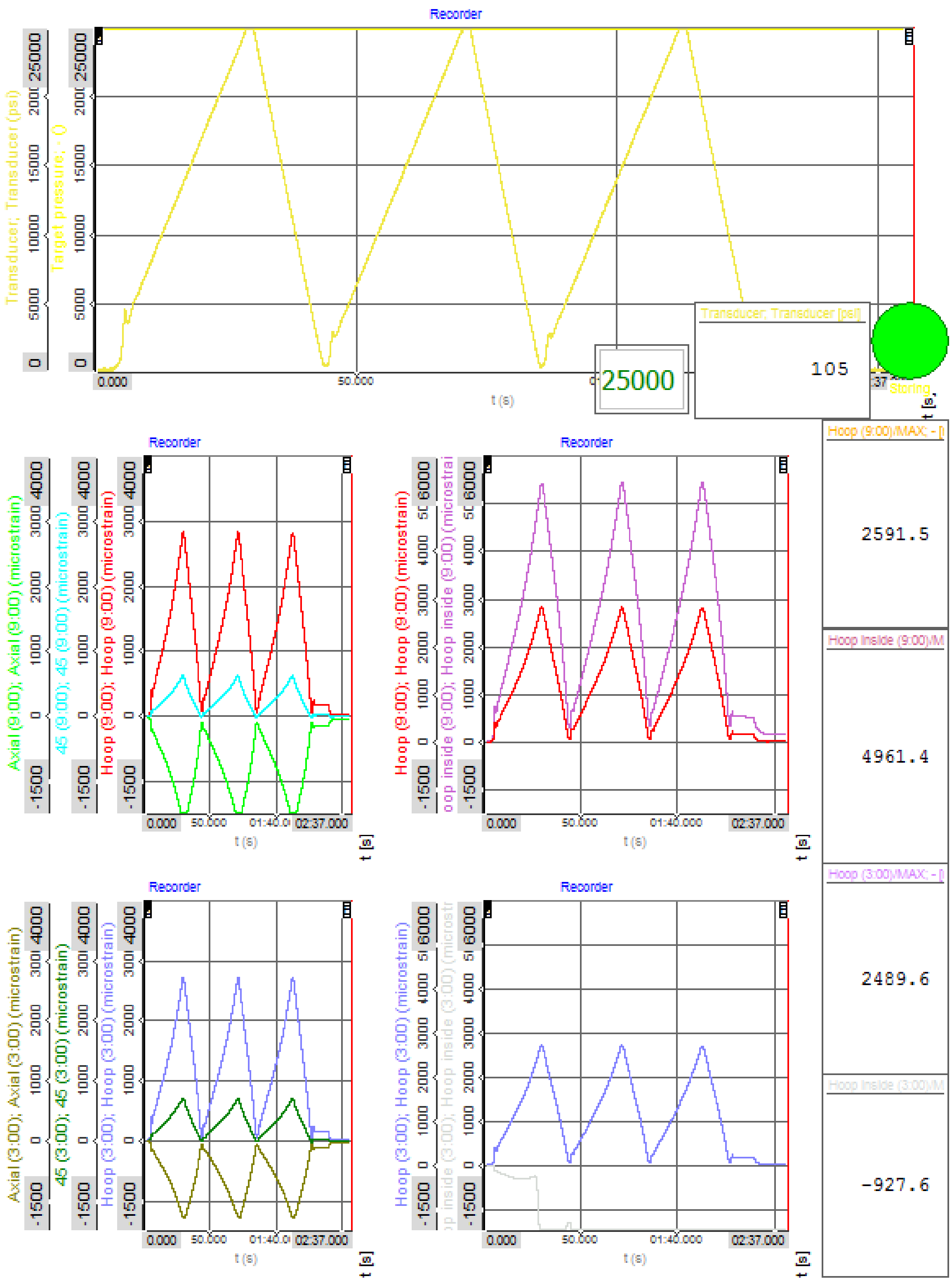

Figure 10: PMC Raw Strain Results for 3 and 9 o'clock (Test Cycle 7)

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Discussion

Mechanical properties for the exact fiber / matrix combination under test were not available. One of the tests conducted in 2005 used an IM7 carbon fiber in polyetheretherketone (PEEK) matrix. For that combination we had material property data and the cylinder test data. Both theoretical and FEA modeling was done on that combination and the results are shown below. Full results of this modeling are available in the references [e].

Hoop Strain ($\mu\varepsilon$)	Theoretical		2005 Specimen		FEA Homogenization		FEA Enriched	
	Inside	Outside	Inside	Outside	Inside	Outside	Inside	Outside
	4068	2489	4516	2400	4057	2488	4082	2522

Table 2: 2005 Strain Results

The fiber used in the 2005 test is the same as this test and hoop strain is a fiber dominated result so the strain values should be similar. Referring to Table 2 we can see that for gages returning valid data we have a range of 5211 to 5621 $\mu\varepsilon$ for the internal and 2580 to 2841 $\mu\varepsilon$ for the external gages. The average strains were 5454 $\mu\varepsilon$ for the internal and 2722 $\mu\varepsilon$ for the external gages. While close to the 2005 data this implies that the new matrix is softer than the PEEK matrix from 2005.

Looking at figure 8 it is readily apparent that the internal and external gages track with each other. This indicates that there is no gap between the steel and the composite. Had a gap formed between the composite and the steel during processing there would have been a delay in the exterior gages responding to the loading. This does not mean that the two are bonded to each other but rather that they are in intimate contact.

Conclusion

One PMC test specimen was instrumented with interior hoop gages and exterior rosette gages and strain data was successfully recorded for multiple cycles to a test pressure for 25,000 psi. The results show that no gap formed between the composite and the steel during processing and that the two are in intimate contact. The repeatability of the gage readings implies that no damage was done to the specimen during cycling.

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a) Keating, John J., "Composite Cylinder Technical Report", Unpublished Benét Internal Technical Report, Benét Laboratories, Watervliet, NY, October 2005.
b) *Test Plan for Hydraulic Testing of a Polymer Matrix Composite Tube,* Benét Laboratories, Watervliet, NY, June 2017.
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e) Macri, M.F., Littlefield, A.G., Root, J.B., Smith, L.B., "Modeling Automatic Detection of Critical Regions in Composite Pressure Vessel Subjected to High Pressure," PVP2018-84168, Proceedings of the ASME Pressure Vessels and Piping Conference, 15-20 Jul 2018, Prague.

Appendix A: Additional Figure

Figure 11: Dead Weight Tester (Model-406-490 / Serial-H10283)

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